PERFORMANCE OF A TWO-HYDROPHONE HEADING SENSOR AND AUV FORMATION FLYING CONTROLLER

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Abstract – **De-centralized formation control is one way to enable the function of multiple Autonomous Underwater Vehicles (AUV's). It is thought that decentralization can lower the requirements on communication for control, and formation-flying would simplify the oversight of large numbers of vehicles operating simultaneously. In this paper, we describe an algorithm that would enable multiple vehicles to maintain formation. Follower vehicles are equipped with a sensor that can determine a relative angular heading to the source of an intercepted acoustic signal from a leader vehicle. This sensor consists of two hydrophones separated by a fixed distance on the follower vehicles. Experiments were conducted to assess the ability of the two-hydrophone sensor to detemine bearing angle in the presence of propellor noise, relative motion with consequent Doppler shift, and a test application in a formation-flying scenario. The effect of using cross-correlation and matched filter signal processing procedures for determination of bearing angle were also compared. It was found that the two-hydrophone sensor could determine bearing angle in the presence of propellor noise, over distances ranging from 9-400m considered in the experiments to an accuracy of approximately 4^{o}. Higher accuracy in bearing angle determination was obtained with matched filter than with cross-correlation signal processing, in spite of relative motion.**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUV's) have shown that they can complete valuable scientific and military missions. In the majority of cases, AUV's have been employed as individuals, or independently in small numbers to complete their tasks. This practice precludes the acquisition of data over large areas in a reasonable time period, because of vehicle/sensor speed limitations, and because the degree of human management grows rapidly when large numbers of independent vehicles are used.

Alternately, it is thought that large numbers of AUV"s could be used to collect data quickly from large areas if they could operate in a decentralized way, minimizing the need for oversight by human operators. One form of decentralized control that can be used to reduce operator oversight is to require that vehicles perform tasks in geometric formation [1]. In this scenario, the operator interface is with the formation, instead of individual vehicles.

A necessity for formation-type decentralized control is that each vehicle must have some knowledge of the relative position of one or more other vehicles in the formation, and, at least one vehicle must sense inertial position. Methods that have been considered to determine relative position include the use of the Wood's Hole acoustic communication and navigation system [2] to exchange position LongBaseLine (LBL) position data [1], or to periodically surface and exchange Global Position Satellite (GPS) data using an RF link [3]. Both of these methods have drawbacks. Acquisition of LBL position data is relatively slow, on the order of 1-2s per fix, and exchange of this information over an acoustic link takes approximately 4 sec using the Wood's Hole system. Consequently, the information arrives infrequently, and with significant time delay. Exchange of GPS data by RF link can take place quickly, but vehicles must interrupt their tasks and surface simultaneously. If the vehicles do not surface simultaneously, some compensation must be applied.

One way to enable AUV formation-flying is to combine a sensor that determines relative heading between two vehicles, and a controller that can utilize this information to maintain formation. A sensor, consisting of a hydrophone located on the bow and stern of an underwater vehicle, has been proposed as a way to determine relative angular heading between two vehicles [4]. This sensor would intercept LBL ranging pings from another vehicle in the formation, extract difference-in-arrival time, and estimate the relative heading between the two vehicles. In this manner, relative heading can be obtained without delay, or consuming acoustic bandwidth. A controller, similar to that proposed in [1], was shown by simulation to be capable of maintaining formation using relative heading data.

In this paper, we present measurements and analysis of the performance of a two-hydrophone sensor. Performance issues include the use of the sensor in the presence of propeller noise and thermal gradient, the effect of Doppler shift caused by relative motion, choice of a proper signal processing technique for extraction of difference-in-arrival time, the effect of separation distance between vehicles, and the performance of a formation-flying controller that utilizes the sensor.

One acoustic modem, used as an source, was located in a stationary position, while a two-hydrophone sensor was mounted to a small surface craft powered by an outboard motor The surface craft intercepted LBL ranging pings from the stationary modem at distances ranging from 9-400m (30-1300ft) and speeds ranging from 1-1.8 m/s (3-6 ft/s). Cross-correlation and matched filter signal processing techniques were applied to extract the difference-in-arrival time to test the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Performance of a Two-Hydrophone Heading Sensor and AUV Formation Flying Controller**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Idaho,Department of Mechanical Engineering,Moscow,ID,83844**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

hypothesis that cross-correlation could compensate for Doppler shift.

We also will report on measurements of the performance of a two-hydrophone sensor used in a formation-flying controller. Two surface craft were used in these experiments. One craft, the leader in the two-craft formation, navigated a pre-determined course using a LBL system. A second vehicle, the follower, was equipped with a two-hydrophone sensor and appropriate control algorithm. The follower vehicle attempted to maintain a geometric formation with the leader vehicle using relative heading information provided by the two-hydrophone sensor.

II. THEORY

A. Determination of Bearing Angle

Consider a two-hydrophone sensor mounted on a follower vehicle shown in Fig. 1. The hydrophones are separated by a distance *d*. A source tranmits an acoustic signal that is received by the two hydrophones. From the signals received at the hydrophones, a difference in arrival time Δt can be caculated using various methods. The bearing angle σ can then be calculated using [4]

$$\sigma = \cos^{-1}\left(\frac{c\Delta t}{d}\right), \tag{1}$$

where *c* is the speed of sound in water. This formula assumes that the source and follower vehicle are at equal depth.

B. Formation-Flying Controller

The formation flying control law set the velocity of the follower using a formation error provided by the two-hydrophone sensor. Consider the leader-follower geometry shown in Fig. 2. The formation requires that the follower maintain a distance a_{ref} behind the leader. Given that the two-hydrophone sensor returns a relative bearing angle, σ, the actual follower distance $\hat{a}$ is

$$\hat{a} = \frac{\Delta}{\tan(\sigma - \varepsilon)}, \tag{2}$$

where ε is the heading of the follower vehicle with respect to the follower waypoint path, and Δ is the perpendicular distance from the follower to the leader waypoint path. The velocity control law used to maintain formation was

$$V_c = V_s + k_v\left(a_{ref} - \frac{\Delta}{\tan(\sigma - \varepsilon)}\right), \tag{3}$$

where V_s is the set-point velocity of the leader, k_v is the control gain, and V_c is the command velocity provided by the control law to the follower vehicle.

III. EXPERIMENTS AND APPARATUS

A. Apparatus

Tests were conducted at the Acoustic Research Detachment [5] located on Lake Pend Oreille Idaho. In tests that required emulation of moving underwater vehicles, surface craft were employed. These surface craft were 7.3m (24 ft) utility boats with outboard engines. They were equipped with GPS, a heading sensor, and a computer configured for data acquisition, control computations, and interface with acoustic apparatus suspended in the water on a fixed mount.

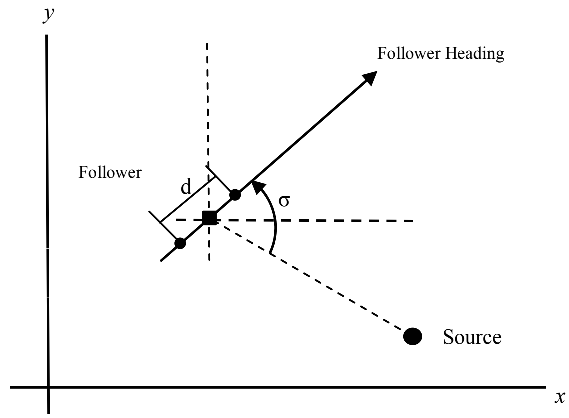

Fig. 1. Two-hydrophone sensor geometry.

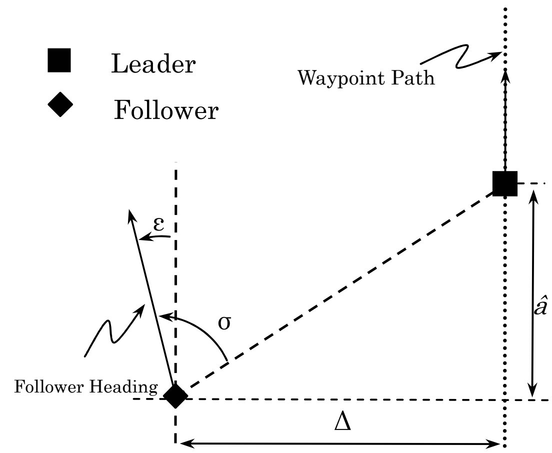

Fig. 2. Leader-follower formation geometry.

The acoustic source and receivers were suspended below the surface at a depth of 2-3 meters. A Woods Hole acoustic micro-modem [2] was used to drive the source transmitter. The source transducer was an ITC-1032 which was omni-directional, broadband, with a resonant frequency of 32 kHz. The source amplitude level was 183 dB (re 1μPa @ 1yd). The navigation ping was a BPSK signal generated by the Woods Hole micro-modem having a carrier frequency of 26 kHz, nominal bandwidth of 4 kHz, and duration of 7 ms. The two-hydrophone sensor consisted of two ITC-8140 hydrophones, separated by a fixed distance of 0.457 m (18 in). The hydrophones were omni-directional and had a flat frequency response from 1 kHz to 40 kHz. The hydrophone voltage signals were anti-alias filtered and sampled simultaneously with 16-bit resolution at sample rate of 65536 Hz.

B. Signal Processing Techniques

The difference in arrival time Δt from the two hydrophone signals was estimated using two separate processing techniques, cross-correlation and matched filter. The matched filter processing is described in [5]. This technique provided an estimation of the difference in arrival time Δt, as well as an estimate of the relative

velocity between source and receiver. Cross correlation processing was similar to the matched filter, except that two measured signals were used in this procedure, as opposed to a measured signal and pre-generated noise-free replica waveforms. Starting with a pair of digitized hydrophone signals, cross-correlation processing is outlined in the following steps:

1. Each hydrophone signal was translated to baseband with a complex sinusoid at 26kHz.
2. A real, symmetric FIR low-pass filter was applied to remove out-of-band interference (such as engine noise).
3. Leading-edge detection was used to locate the transmitted acoustic signal within each filtered hydrophone data stream. The data was compared to a fixed threshold value and when exceeded, was truncated in time with a rectangular window having the length slightly longer the transmitted waveform.
4. The resulting analytic signals were then cross-correlated producing a sampled complex correlation output.
5. The amplitude of the complex cross correlation was computed, and the sample maximum is located.
6. To overcome sample-interval round-off errors, a parabola was fit to the 3 points surrounding the sampled peak. The desired difference in arrival time Δt was computed from the vertex of the estimated parabola.

Compared to matched filter processing, the cross correlation approach allows simpler and in some ways more robust processing. No Doppler compensation is required due to the close proximity of the two hydrophones relative to the source transmitter. This technique achieves best accuracy using broadband acoustic waveforms such as Phase-shift Keyed (PSK) or Linear Frequency Modulated (LFM), which are commonly used for acoustic ranging. Cross-correlation requires knowledge only of the basic characteristics of the transmitted waveform, such as approximate carrier frequency, bandwidth, and duration. For example, no apriori knowledge of transmitted PSK ID codes is required.

C. Procedures

Two sets of experiments were performed. The first set was designed to determine the effect of propellor noise, relative motion, and signal processing technique on the performance of the two-hydrophone sensor. The intent of the second set of experiments was to test the use of the two-hydrophone sensor with a formation-flying controller.

For the first set of experiments, the two hydrophone sensor was installed on a surface craft, and a Woods Hole navigation source was suspended from a tethered stationary moorage. The surface craft drove past the navigation source at at velocities ranging from 1-1.8 m/s (3-6 ft/s) while using the two-hydrophone sensor to determine the relative bearing angle to the source. These experiments were conducted in October, when gradients in sound speed of less than 1 m/s per meter of depth change are typical within the upper 3 meters of water.

In the second set of experiments, two surface craft were used. One craft, designated as the leader, was driven by a human driver along a straight line course using GPS navigation at a constant velocity of 1.05 m/s (3.5 ft/s). As the leader craft navigated the straight line course, it emitted ranging pings with a Woods Hole navigation source. Simultaneously, a second surface craft, equipped with a two-hydrophone sensor, was driven by a human operator on a course parallel to the leader. The driver of the follower vehicle also navigated a straight line course by GPS, however, the velocity was determined by a computer readout of the control law (3). These experiments were conducted in July, when sound speed gradients of 10-15 m/s per meter of depth change are common within 3 meters of the surface.

IV. RESULTS AND DISCUSSION

A. Bearing Angle Determination in the Presence of Propellor Noise

Fig. 3 shows one example of the waveforms received by the two-hydrophone sensor, and subsequent steps in the signal processing procedure used to extract the difference in time of arrival Δt using cross-correlation. In part a of Fig. 3, the raw digitized signals from each of the hydrophones are plotted versus time on the horizontal axis. Barely visible in the two hydrophone signals is the arrival of the navigation ping at a time of approximately 1.25s. The signals were then shifted to base-band by demodulation, and low-pass filtered. After these operations, the hydrophone signals were transformed to those that are plotted in part b of Fig. 3. In part b of Fig. 3, the arrival of the navigation ping at 1.25s is clearly visible. A cross-correlation of the signals contained in part b of Fig. 3 is shown in part c. For part c, the horizontal axis is lag time in μs. A peak in correlation at a lag time of 72 μs is clearly visible. In general, our measurements showed that it was feasible to estimate relative bearing angle from the difference in arrival time Δt in the presence of propeller noise.

B. Bearing Angle Determination with Relative Motion

Experimental measurements of bearing angles are shown in Fig. 4. In part a of Fig 4, GPS coordinates of the surface craft and dock are shown for an example run. In this run, the distance from the surface craft to the dock varied from 90m to 400m, and the velocity of the surface craft was approximately constant at a value of 1.5 m/s (4.9ft/s). Note that the dock drifted back and forth during the run. In part b Fig. 4, bearing angles σ_{cc} and σ_{mf} as determined with the two-hydrophone sensor using cross-correlation and matched-filter respectively are plotted on the vertical axis versus time on the horizontal axis. The bearing angles angles σ_{cc}, and σ_{mf} are marked with open circles and a cross (×) symbol respectively. Also plotted on the vertical axis of part b Fig. 4 is the indicated bearing angle σ as determined by GPS coordinates of the dock and surface craft and a heading sensor located on the surface craft. The indicated bearing angles are denoted by a point (•) symbol.

In general, the bearing angles determined by the two-hydrophone sensor were with 9° of the indicated equivalent determined by GPS. This compared with a standard deviation error of 2° as determined in earlier

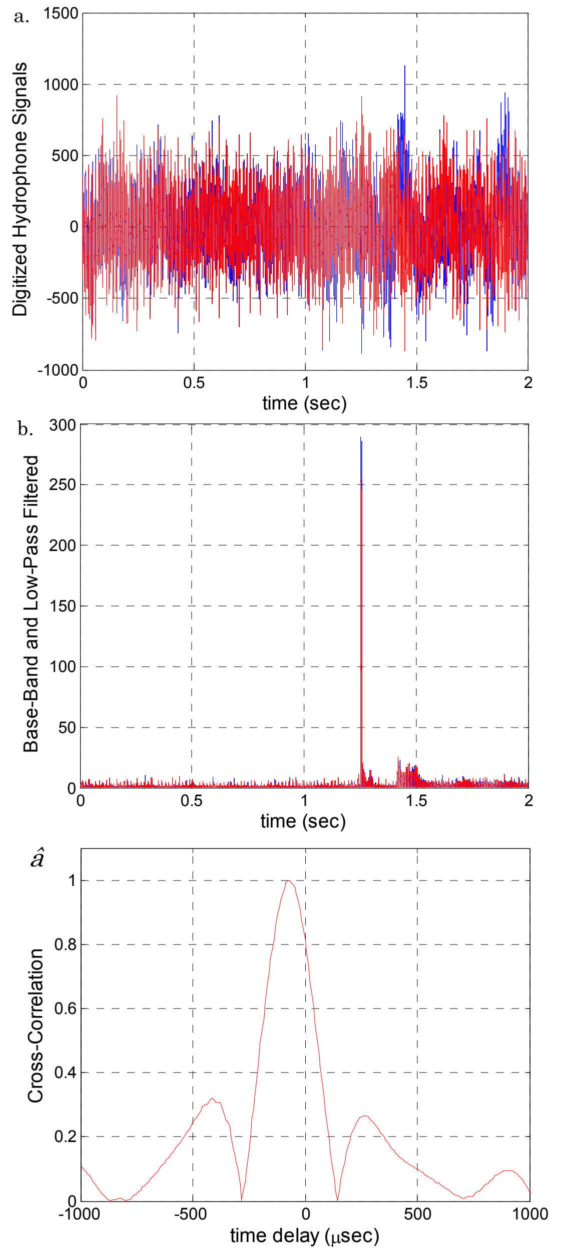

Fig. 3 Processing of hydrophone signals. a) Raw waveforms, b) waveforms after base-band demodulation and low-pass filtration, c) cross correlation of signal in part b.

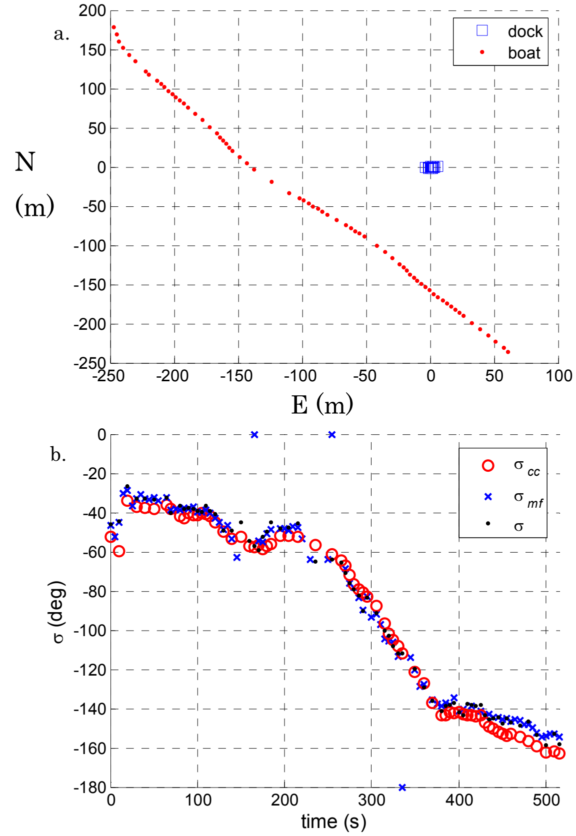

Fig. 4 GPS track positions and bearing angle determinations from relative motion test. a) GPS track positions of a surface vehicle and floating dock. b) bearing angles determined with cross correlation and matched filter signal processing.

static tests [4] with the same two-hydrophone sensor using cross-correlation signal processing. It was observed that the matched filter processing procedure performed better than cross-correlation for determination of relative bearing angle. The difference between indicated bearing angle and that determined with the two-hydrophone sensor using matched filter signal processing was a maximum of 4^{o}, while when using cross-correlation, the difference was as great as 9^{o}. This was unexpected, as it was hypothesized that cross-correlation automatically compensates for Doppler shift, while the matched filter technique requires compensation for Doppler. The reasons for this difference in performance are at the time unknown.

C. Formation-Flying

A result from the leader-follower formation-flying experiments is shown in Figs. 5 and 6. The surface craft were instructed to travel parallel straight paths 15.25 meters apart with the follower maintaining a distance of a_{ref}=15.25m behind the leader. In Fig. 5, the GPS position tracks for the leader and follower are shown, along with the intended waypoint paths. The actual follow distance, $\hat{a}$, recorded during the test was extracted from the data in Fig. 5 and plotted verses elapsed time with the desired follow distance a_{ref} in Fig. 6. In Fig. 6, it is apparent that the follower craft was approximately 20m ahead of the leader craft at the beginning of the test. Initially, the follower fell behind the leader as would be desired. However, as time progressed, the follower assumed a position that was approximately 50m behind the leader, a larger distance than the a_{ref}=15.25m required by the controller.

Two possible causes for the poor formation-flying performance include inaccurate velocity response by the operators of the boats and incorrect data provided by the two hydrophone sensor. The leader boat was instructed to hold a constant velocity of 1.05 m/s (3.5 ft/s), and actually averaged 1.16 m/s (3.8 ft/s) over the latter half of the test. This represented a 10% error which contributes but did not fully account for the large follow distance

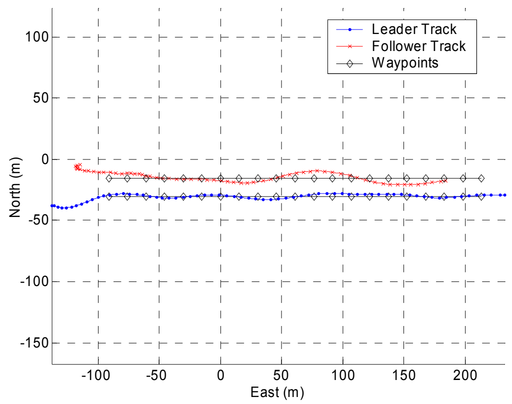

Fig. 5. Courses followed during leader-follower formation-flying experiment with 2-hydrophone sensor.

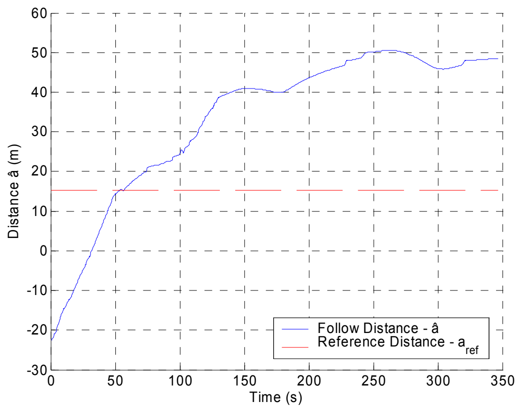

Fig. 6. Actual follow distance recorded during leader-follower formation-flying experiment with 2-hydrophone sensor.

shown in Fig. 6. The follower had similar performance to the leader staying within 10% of the recommended velocity. Therefore, the problem was not primarily based in the operator's inability to follow the recommended velocity, but in its derivation. During the first one hundred seconds, the two-hydrophone sensor only returned two valid bearing angles out of seven attempted. In addition, the two valid bearing angles were both greater than 110^o, which properly caused the follower to slow down and the follower fell behind the leader. After 100 seconds of testing, the two-hydrophone sensor improved to eleven valid bearing angles out of fifteen attempted, nine of which were in the 22^o to 45^o range which caused small formation corrections. GPS position data reveals that the true relative bearing angles ranged from 5^o to 35^o, which corresponds to larger corrections needed than supplied. The two-hydrophone sensor overestimated the relative bearing angle, which caused the controller to assume the leader was closer than it really was, and recommend slower velocities than were needed.

V. CONCLUSIONS

Tests with a two-hydrophone sensor suspended 2-3m below a surface craft showed that relative bearing angles could be measured to an accuracy of approximately 4^o in the presence of low frequency propellor noise, Doppler shift associated with relative velocities on the order of 1m/s, and separation distances ranging from 9-400 m. Use of matched-filter signal processing exceeded the performance of cross-correlation for determination of relative bearing angle with the two-hydrophone sensor.

Acknowledgments

The authors gratefully acknowledge the support of the Office of Naval Research under the award "Developing Fleets of Autonomous Underwater Vehicles" No. N00014-05-1-0674. Help with graphics provided by Jesse Kappmeyer, was also greatly appreciated.

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